Calculations of nucleon electric dipole moments on a lattice with chiral fermions

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SNOWMASS21-RF3_RF0-TF5_TF0-CompF2_CompF0_Syritsyn-077.pdf

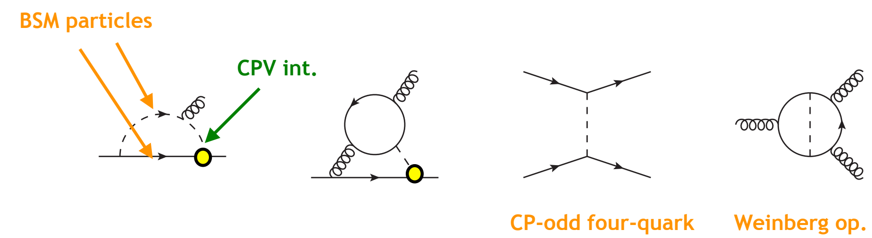
The physics / basic idea of the LOI

- The first principile Lattice QCD calculation connecting quark/gluon-level (effective) interaction to CP-violating nucleon EDM and matrix elements which is essential ingredients to interpret the future EDM experiments

- Physics outcome :

$$d_{n,p} = \sum_q g^q_{Tn,p} d_q + d^{\bar{\theta}}_{n,p} \bar{\theta}_{\mathrm{QCD}} + d^{\delta_W}_{n,p} \delta_W + \sum_q d^{\delta_q} \delta_q + \dots$$

θ-EDM mixed to higher-dim ops



- Cross frontiers :
  TF05 (Lattice Gauge Theory),
  CompF2 (Theoretical Calculation and Simulation)

$$\mathcal{L}^{\cancel{CP}}_{eff} = \frac{g_s^2}{32\pi^2} \bar{\theta} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ dim=4, θ_{QCD}

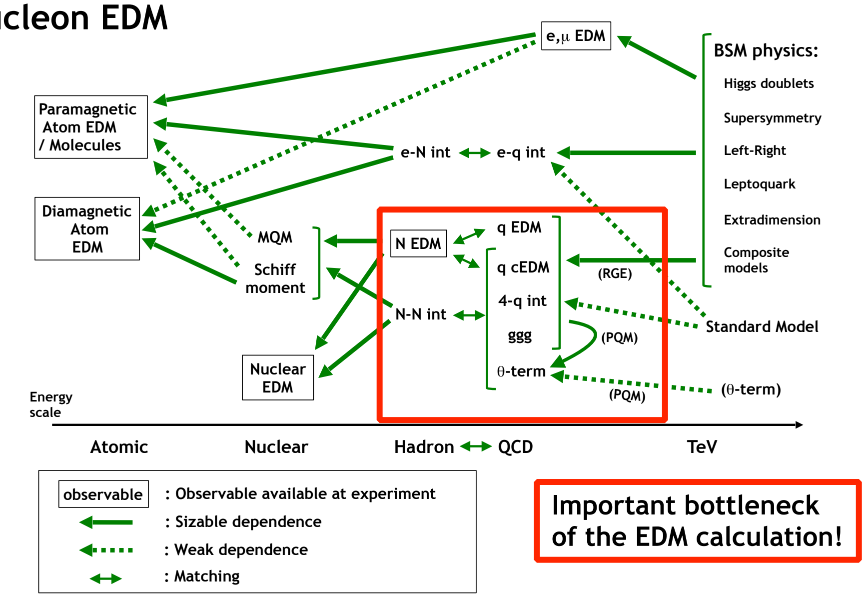
$$- \frac{i}{2} \sum_{i=u,d,s} \tilde{d}_i \bar{\psi}_i G \cdot \sigma\gamma_5 \psi_i$$ dim=5, chromo EDM

$$- \frac{i}{2} \sum_{i=e,u,d,s} d_i \bar{\psi}_i F \cdot \sigma\gamma_5 \psi_i$$ dim=5, e, quark EDM

$$+ \omega f^{abc} G_{\mu\nu,a} G^{\mu\beta,b} G^{\nu,c}_{\beta}$$ dim=6, Weinberg three gluon

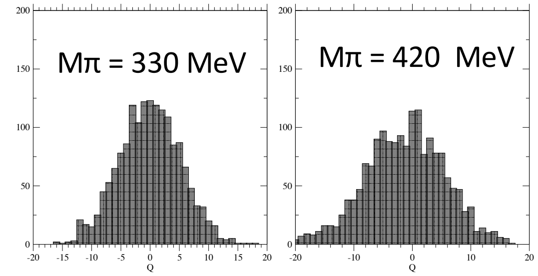
$$+ \sum C_i^{(4q)} \mathcal{O}_i^{(4q)}$$ dim=6, Four-quark operators

•**Nucleon EDM**

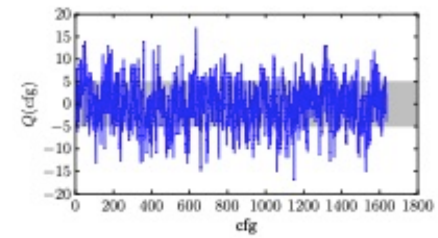


[N. Yamanaka, et al. Eur. Phys. J. A53 (2017) 54, Ginges and Flambaum Phys. Rep. 397, 63, 2004]

What is required for the LOI to succeed



- EDM Experiments (proton, neutron, ….)
- LQCD side :
  - High Performance Computing resources
    - θ-EDM noisy needs a lot of statistics, ~1k-10 k level QCD configurations, $\theta G_{\mu\nu}\tilde{G}_{\mu\nu} = \theta Q_{\rm top}$
    - topological charge needs to be well sampled
    - (sea) quark mass dependence $\langle Q^2_{\rm top}\rangle \propto m_q$

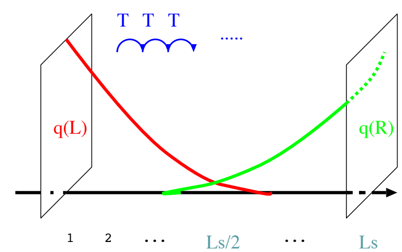


Chiral Lattice Quark is a must, as θ and chromo EDM is sensitive to the chiral symmetry violation from dimension-5 lattice artifact.

U(1)$_A$ rotation:

$$m\bar{q}q + \theta G\cdot\tilde{G} + a\bar{q}G\cdot\sigma q$$

$$\to m\bar{q}q + i\theta\bar{q}\gamma_5 q + a\bar{q}G\cdot\sigma q + a\theta\bar{q}\tilde{G}\cdot\sigma q$$



[S. Aoki, A. Gocksch, A. V. Manohar, and S. R. Sharpe, Phys. Rev. Lett. 65, 1092 (1990)]

- Could share most of Lattice configurations (QCD vacuum samples) with other LQCD calculation
- Man-power (both Lattice theorists and software supports)

What do you plan to do during Snowmass

- Θ A lot of LQCD trials, 50-100% error at physical quark mass
  - External electric field method
  - Restrict correlation b/w θ Qtop and nucleon on lattice
  - Other ways to control statistical fluctuations
  - Devoted QCD configuration with (imaginary) θ
- Quark-EDM : best shape ~ 3-5 % error (except strange quark) [Bhattacharya et al, PRL 115, 212002 (2015)] [Yamanaka et al. JLQCD, PRD 98, 054516 (2018)]
- Quark chromo EDM : unrenormalized lattice number evaluated (~20% stat error for unrenormalized value), also non-perturbative renormalization available [Bhattacharya et al, PRD92, 114026 (2016)]
- Weinberg operator : started [Shindler et al, PRD92, 094518 (2015)] , also renormalization proposed [Cirigliano et al, arXiv:1711.04730] , uncertainty is very large
- 4-quark operators : not explored yet

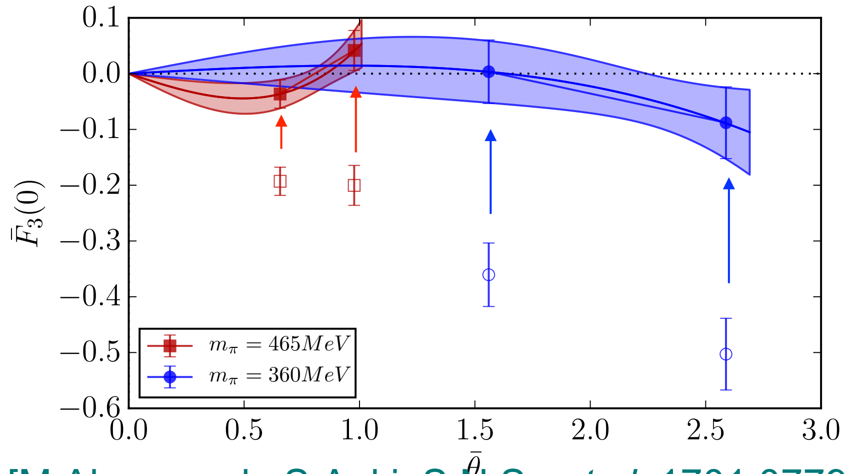
What do you hope to get out of Snowmass

- nEDM and proton storage ring experiments are critical
  - Results directly connected to origin mystery of the Universe
  - Discovery would provide huge benefit to HEP community
    And
- In the next decade, nucleon EDM may be in good shape
- proton in 10 years, even greater sensitivity
- Atomic/molecular EDMs (e.g. Hg, Ra, ThO, …): need to collaborate with nuclear and atomic physicists (effective theory, shell-model etc.)

θ_{QCD}-induced nEDM : Status

Correction to previous results:

$$[F_3]_{\text{true}} = \text{“}F_3\text{”} + 2\alpha F_2$$



[M.Abramczyk, S.Aoki, S.N.S., *et al*, 1701.07792]

		m_π [MeV]	m_N [GeV]	F_2	α	$\tilde{F}_3$	F_3
[ETMC 2016]	n	373	1.216(4)	$-1.50(16)^a$	$-0.217(18)$	$-0.555(74)$	0.094(74)
[Shintani et al 2005]	n	530	1.334(8)	$-0.560(40)$	$-0.247(17)^b$	$-0.325(68)$	$-0.048(68)$
	p	530	1.334(8)	0.399(37)	$-0.247(17)^b$	0.284(81)	0.087(81)
[Berruto et al 2006]	n	690	1.575(9)	$-1.715(46)$	$-0.070(20)$	$-1.39(1.52)$	$-1.15(1.52)$
	n	605	1.470(9)	$-1.698(68)$	$-0.160(20)$	0.60(2.98)	1.14(2.98)
[Guo et al 2015]	n	465	1.246(7)	$-1.491(22)^c$	$-0.079(27)^d$	$-0.375(48)$	$-0.130(76)^d$
	n	360	1.138(13)	$-1.473(37)^c$	$-0.092(14)^d$	$-0.248(29)$	$0.020(58)^d$

After removing the spurious contribution,

- *no lattice signal for θ_{QCD}-induced nEDM ⇨ d_N is very small, compatible with zero*
- *RESOLVED conflict with phenomenology values, lack of m_q scaling*

Nucleon "Parity Mixing"

With proper definition of $F_{2,3}$ [M.Abramczyk, S.Aoki, SNS, *et al,* 1701.07792]

- coupling of E,B to spin in the forward limit

$$\langle H_{\rm int}\rangle = eA_\mu\langle J^\mu\rangle = -\frac{eG_M(0)}{2m_N}\vec\Sigma\cdot\vec H - \frac{eF_3(0)}{2m_N}\vec\Sigma\cdot\vec E$$

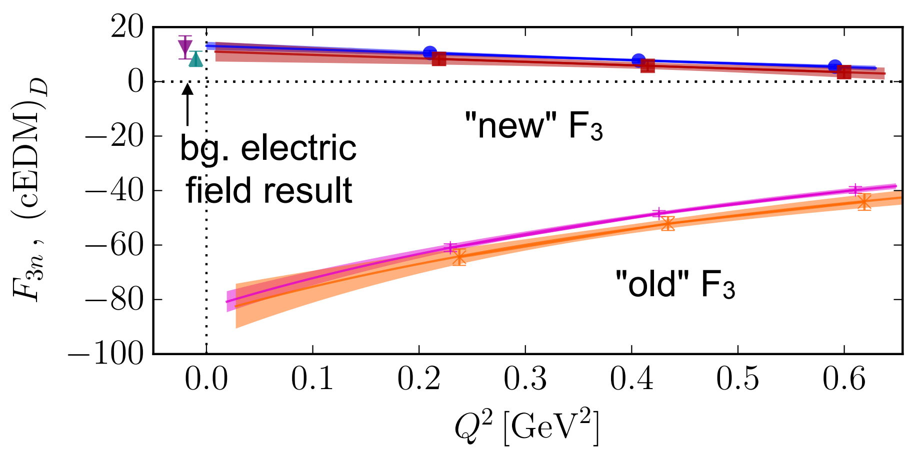
- poles of the Dirac operator in bg. electric & magnetic fields

$$\mathcal{L}_N = \bar N\big[i\not\partial - me^{-2i\alpha\gamma_5} - Q\gamma_\mu A^\mu - (\tilde\kappa + i\tilde\zeta\gamma_5)\frac{1}{2}F_{\mu\nu}\frac{\sigma^{\mu\nu}}{2m_N}\big]N$$

$$E_N(\vec p=0) - m_N = -\frac{\kappa}{2m_N}\vec\Sigma\cdot\vec H - \frac{\zeta}{2m_N}\vec\Sigma\cdot\vec E + O(\kappa^2,\zeta^2)$$

with $\kappa + i\zeta = e^{2i\alpha\gamma_5}(\tilde\kappa + i\tilde\zeta)$

- Numerical test: compare EDFF with mass shift in uniform bg. electric field



d-cEDM induces large mixing
$\alpha_D \approx 30(0.2)$

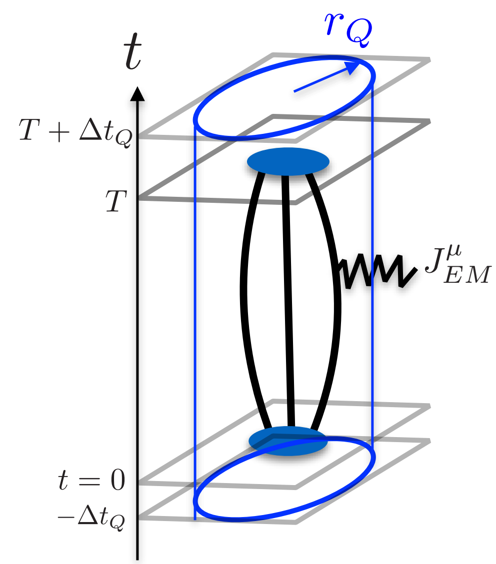
Large F_{2n} contribution to "F_{3n}"
$$\text{“}F^D_{3n}\text{”} = [F^D_{3n}]_{\rm true} - 2\alpha_D F_{2n}$$

Noise reduction for θ-induced EDM

Statistical error $\sim$ V_4

Topological charge: $Q \sim \int_{V_4} G\tilde{G}, \quad \langle Q^2 \rangle \sim V_4$

nucleon EDM: $F_3 \sim \langle Q \cdot (N J^{\mu}_{EM} \bar{N}) \rangle$



Constraining to the fiducial volume for Q

$$Q \sim \int_{V_Q} d^4x q(x)$$

- 4d spherical [K.-F. Liu, et al, 2017]

  $$|x_Q - x_{sink}| < R$$

- truncation in t-direction [Shintani et al 2015, Guo et al 2019]

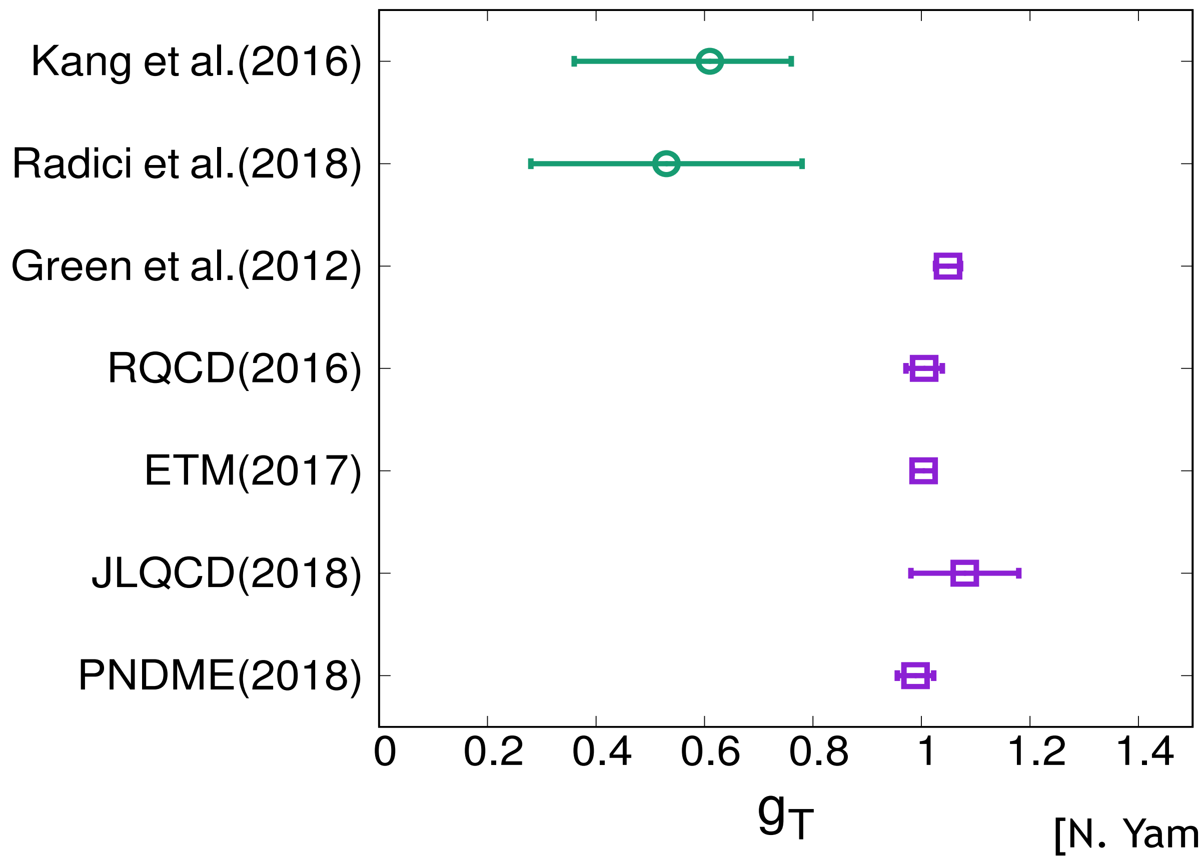
  $$|t_Q - t_J| < \Delta t$$

- 4d “cylinder” (new)

  $$V_Q : |\vec{x}| < r_Q, \quad -\Delta t_Q < t_0 < T + \Delta t_Q$$

Recent results: the isovector tensor charge

$$g_T \equiv \frac{1}{2m_N}\langle p|\bar{u}i\sigma_{03}\gamma_5 u - \bar{d}i\sigma_{03}\gamma_5 d|p\rangle = \delta u - \delta d,$$



[N. Yamanaka, 1902.00527]

All lattice results are very accurate and show consistency among them.
The lattice error is much smaller than phenomenological estimates.
Lattice : important input for nEDM